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HIGH RESOLUTION WAVEFRONT CONTROL OF HIGH-POWER LASER SYSTEMS

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Most large laser systems at Lawrence Livermore National Laboratory require adaptive optics to correct for internal aberrations in these high-power systems. Many of these systems, including those being developed for Inertial Confinement Fusion and Laser Isotope Separation, already contain adaptive optics based on conventional deformable mirror technology. Increasing requirements for laser system applications are currently driving wavefront control technology toward increased spatial frequency capacity, as well as reduced system costs. We will present recent progress in the utilization of liquid crystal spatial light modulator technology appropriate for high-resolution wavefront control of high-power laser systems.

1 Introduction

Nearly every new large-scale laser system application at LLNL has requirements for beam control which exceed the current level of available technology. For applications such as inertial confinement fusion, laser isotope separation, laser machining, and laser the ability to transport significant power to a target while maintaining good beam quality is critical.

There are many ways that laser wavefront quality can be degraded. Thermal effects due t the interaction of high-power laser or pump light with the internal optical components or with the ambient gas are common causes of wavefront degradation. For many years, adaptive optics based on thing deformable glass mirrors with piezoelectric or electrostrictive actuators have be used to remove the low-order wavefront errors from high-power laser systems. These adaptive optics systems have successfully improved laser beam quality, but have also generally revealed additional high-spatial-frequency errors, both because the low-order errors have been reduced and because deformable mirrors have often introducted som high-spatial-frequency components dut to manufacturing errors. Many current and emerging laser applications fall into the high-resolution category where there is an increased need for the correction of high spatial frequency aberrations which requires correctors with thousands of degrees of freedom.

The largest Deformable Mirrors currently available have less than one thousand degrees of freedom at a cost of approximately $1M. A deformable mirror capable of meeting these high spatial resolution requirements would be cost prohibitive. Therefore a new approach using a different wavefront control technology is needed. One new wavefront control approach is the use of liquid-crystal (LC) spatial light modulator (SLM) technology for the controlling the phase of linearly polarized light. Current LC SLM technology provides high-spatial-resolution wavefront control, with hundreds of thousands of degrees of freedom, more than two orders of magnitude greater than the best Deformable Mirrors currently made. Even with the increased spatial resolution, the cost of these devices is nearly two orders of magnitude less than the cost of the largest deformable mirror.

2 SLM Technology

The LC SLM devices utilized in the investigations described in this paper are a type of optically-addressed (OA) nematic LC SLM currently available from both Jenoptik and Hammamatsu. These devices are capable of phase correction of greater than one wave at visible and near-infra-red wavelengths. An OA_LC_SLM consists of a thin-film sandwich structure, shown in figure 1, with an amorphous silicon photo-semiconductor Amorphous Silicon (α-Si), a parallel aligned nematic liquid crystal, a dielectric mirror, and a pair of transparent electrodes on glass substrates. The voltage applied to the electrodes is divided between photo-semiconductor and liquid crystal layers, depending on the illumination intensity, thereby enabling 2D-image modulation of the refractive index of the LC.

To activate the OA_LC_SLM the amorphous silicon (α-Si) layer must be exposed to an image pattern. The resolution of control of the SLM is directly proportional to the resolution of the image pattern generated onto the α-Si layer up to some limit. In the state where no pattern is incident on the device, the impedance of the α-Si layer is very high, with or without the voltage applied across the electrodes. When an image pattern is projected onto the α-Si layer, the impedance of the α-Si reduces in proportion to the light intensity in that region and the voltage applied to the liquid crystal increases, causing electro-optic modulations in the liquid crystal layer due to the movement of liquid crystal molecules.

The resolution of the image projection system (which in this case is based on a liquid crystal display or LCD) determines at the resolution at which the SLM will effect the read beam. The currently available devices have the capability of providing control of up to 50 line-pairs/mm. The device from Jenoptik comes with a 832 x 624 LCD and Hamamatsu provides a 640 x 480 LCD. The operational configuration is shown in Figure 2.

These devices work with polarized light. The maximum phase shift is obtained when the polarization of readout light is parallel to the axis of the liquid crystal molecules. When the polarization of readout light is perpendicular to the axis of the liquid cyrstal molecules the phase shift is negligible.

3 Phase Reconstruction Methods

Accurately controlling waverfront phase with a high-spatial-resolution wavefront correction device requires a high-spatial-resolution wavefront measurement capability. This can be provided with a standard Shack-Hartmann wavefront sensor using available high-density lenslet arrays. However, computational requirements for traditional matrix-vector multiply wavefront reconstruction algorithms using slope data from a Shack-Hartmann (or other wavefront slope) sensor scale as N^2 where N is the number of phase points. For large N, greater than 10^3 this begins to become impractical. Since the slope measurement of the Schack-Hartmann sensor can be represented by a spatial filtering operation, an inverse filter can be designed to directly recover the wavefront from the slope data. This allows the reconstruction process can then be implemented as a 2D convolution operation using FFT's which scale as $N\log_2 N$. We have used computer simulations to demonstrate that for 4096 phase points the FFT-based algorithm is ~30 times faster than a matrix multiply (Figure 3). A similar approach has been utilitzed by Chanteloop et al[3] with a shearing interferometer as the wavefront slope sensor.

We have used the FFT-based reconstruction method in lab experiments using the test-bed described in Figure 3 with a Shack-Hartmann sensor of 1Kx1K pixels containing a lenslet array with greater than 2500 lenslets. To verify that the algorithm would accurately represent the pattern generated, a checkered phase pattern was produced on the LC SLM and Shack-Hartmann image data was recorded (figure 4a). The wavefront phase was then reconstructed using the FFT-based method (figure 4b). The resulting phase reconstruction accurately depicted the applied checkered phase pattern. Additional tests were performed using different phase patterns with each reconstruction accurately representing the applied pattern.

4 SLM Experimental Test Bed

A test-bed, shown schematically in Figure 5, has been assembled to allow the evaluation of SLM devices for high-spatial-resolution spatial wavefront control. This test-bed provides the capability to place both low-order and high-order aberrations onto a beam, to detect these aberrations with a high-spatial-resolution Shack-Hartmann sensor, and to correct these phase aberrations using the OA_LC SLM. This process is currently implemented using multiple computer systems in a human-in-the-loop closed-loop operation.

5 Experimental Results

An initial set of experiments has been completed using the Jenoptik OA_LC SLM. In these experiments, an aberration was placed into the main beam path (Figure 6a) and the resulting high-resolution Shack-Hartmann image was processed using the FFT-based method to reconstruct the phase (Figure 6b). From the reconstructed phase an appropriate correction image was generated and applied via the SLM. The applied correction produced a significantly improved far field spot, Figure 6c. The corrected wavefront was reanalyzed with the same methods (Figure 6d) and a significant improvement was observed iin the reconstructed phase image.

Similar experiments utilizing the Hamamatsu AO_LC SLM are currently underway in the SLM test-bed with some modifications to improve the collimation of the write-beam from the back-light diode and thereby improve the correlation between the image pattern genrated on the LCD and the phase correction produced by the SLM.

Design for the introduction of an OA_LC_SLM into a high-powered short-pulse laser is also currently in progress. The OA_LC_SLM will be used to correct high-spatial-frequency phase errors in the front end of the Petawatt Short-Pulsed Laser[4,5]. In this experiment we will be testing the ability of the SLM to correct for high-spatial-frequency errors and the effects on transport of the correction through the spatial filters of the system. The OA_LC_SLM will also be inserted into the system in two additional locations that have a higher beam fluence to evaluate the performance in high-power conditions and to determine the damage threshold.

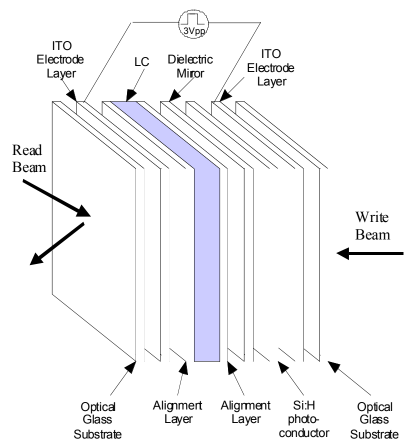


Figure 1 Anatomy of SLM

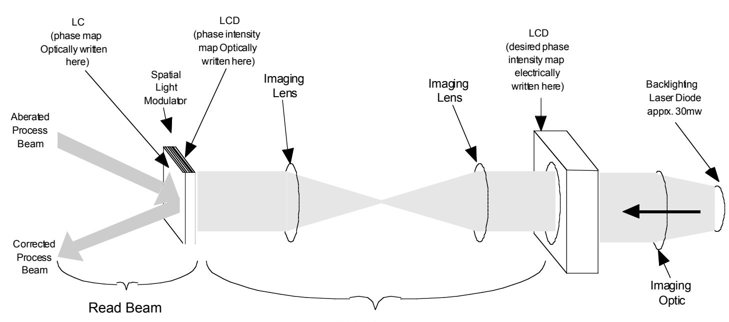
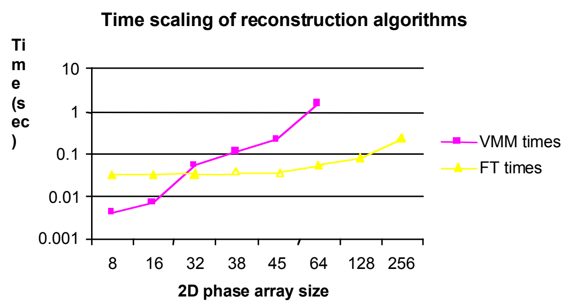
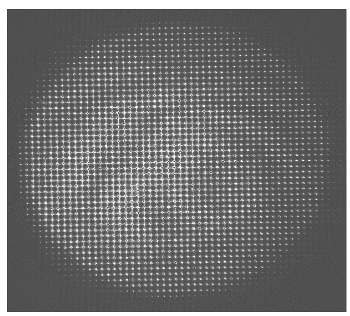


Figure 2 SLM Operation



Times for single R10000 CPU in View

Figure 3 Phase Array Size versus Computation Requirements



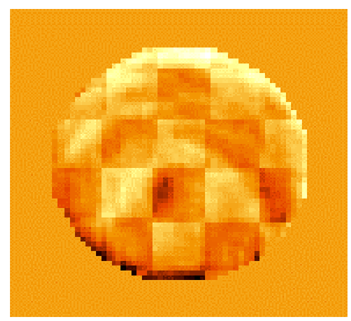


Figure 4a High-Resolution Hartmann Sensor

Figure 4b Reconstructed Wavefront using FFT's

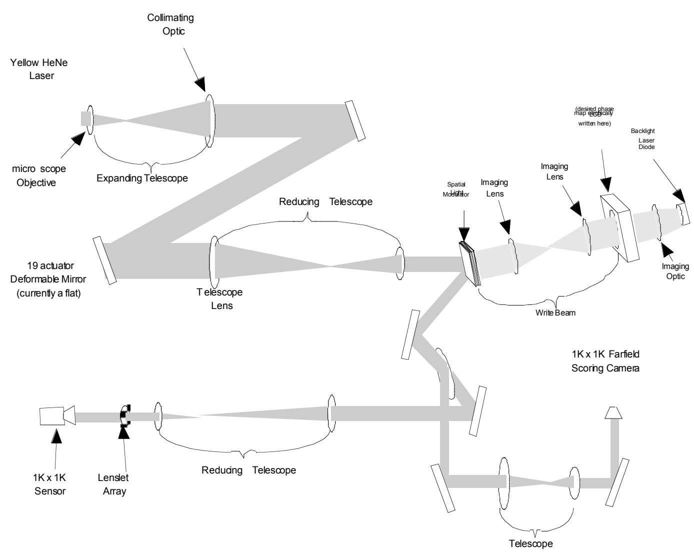


Figure 5 SLM Test Bed

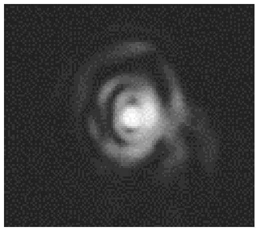


Figure 6a Aberrated far-field

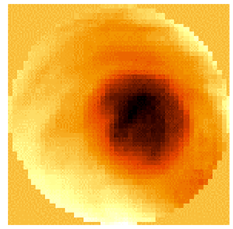


Figure 6b Aberrated Wavefront

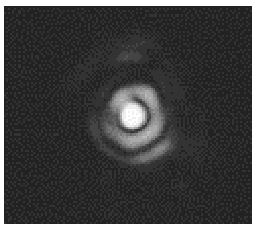


Figure 6c Corrected far-field

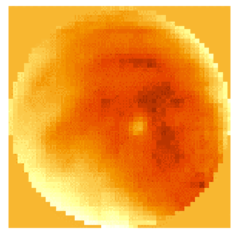


Figure 6d Corrected Wavefront

6. Acknowledgements

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